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JCAA/JG-PP LEAD-FREE SOLDER PROJECT: -20˚C to +80˚C THERMAL CYCLE TEST

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ABSTRACT

Thermal cycle testing is being conducted by Boeing Phantom Works (Seattle) for the Joint Council on Aging Aircraft/Joint Group on Pollution Prevention (JCAA/JG-PP) Lead-Free Solder Project. The JCAA/JG-PP Consortium is the first group to test the reliability of lead-free solder joints against the requirements of the aerospace/military community.

The solder alloys selected for test were:

Sn3.9Ag0.6Cu for reflow and wave soldering
Sn3.4Ag1.0Cu3.3Bi for reflow soldering
Sn0.7Cu0.05Ni for wave soldering
Sn37Pb for reflow and wave soldering

Test vehicles were assembled using these solders and a variety of component types and the test vehicles are being thermally cycled (from -20°C to +80°C). To date, 11,100 thermal cycles have been accumulated.

The solder joints on the components are being electrically monitored using event detectors and any solder joint failures are recorded on a Labview-based data collection system. The failures of a given component type attached with SnPb solder will be compared to the failures of the same component type attached with lead-free solders by using Weibull analysis.

Key Words: thermal cycling, lead-free solders, reliability

BACKGROUND

Recently, legislation has been passed in Europe to ban the use of lead (and other materials) in new electronics starting 1 July 2006. The legislation actually banning lead is called the RoHS (Restriction of Hazardous Substances). The legislation that governs the re-use and recycling of electronics waste is called the Waste from Electrical and Electronic Equipment (WEEE) Directive.

Japan also has become focused on lead-free electronics. Many of the major electronics companies (e.g., Hitachi, NEC, NTT, Panasonic) have announced lead reduction targets and the move to lead-free electronics is supported by JEITA (the Japan Electronics and Information Technology Industries Association). These companies view lead-free as a marketing tool that will allow them to gain market share from their foreign competitors.

Aerospace and military electronics are currently exempt from the European legislation. However, as the international commercial electronics industry changes over to lead-free technology in order to satisfy the European legislation, it will become increasingly difficult for aerospace and military programs to procure electronics made with SnPb solder. For this reason, a DoD sponsored consortium was founded in May of 2001 to evaluate lead-free solders and finishes and to determine whether they are suitable for use in high reliability electronics. This consortium is jointly managed by the Joint Council on Aging Aircraft (JCAA) and the Joint Group on Pollution Prevention (JG-PP). The consortium's project is called the JCAA/JG-PP Lead-Free Solder Project and it boasts members from all branches of the Armed Services, NASA, Boeing, Rockwell-Collins, Raytheon, BAE Systems, ACI, Lockheed Martin, Texas Instruments, NCMS, JPL, Sandia National Labs and Marshall Space Flight Center among others.

The consortium wrote a test plan called the Joint Test Protocol (JTP[1]) which describes the testing to be done. The testing includes thermal cycling, thermal shock, vibration, mechanical shock, combined vibration/thermal cycling, electromigration, SIR, salt fog and humidity testing.

A test vehicle was designed and the lead-free solders to be tested were chosen. The solder selection process was documented in the Potential Alternatives Report (PAR[2]).

The test vehicle is a six-layer circuit board 14.5 inches wide by 9 inches high by 0.090 inches thick. A break-off coupon populated with chip resistors and chip capacitors is attached to one side of the main test vehicle. With the break-off coupon removed, the main test vehicle is 12.75 in. by 9 inches in size and is populated with 55 components consisting of ceramic leadless chip carriers (CLCC's), plastic leaded chip carriers (PLCC's), TSOP's, TQFP's, BGA's, and PDIP's (Figure 1). The components contain internal wire bonds so that once mounted on the test vehicle, each component completes an electrical circuit that can be monitored during testing. Failure of a solder joint will cause a break in the electrical circuit that can be detected by an event detector. Each test vehicle also has a daisy-chain of twelve 0.016 inch diameter plated thorough holes so that the reliability of the holes can be determined. The plated through holes were filled with solder during the wave solder operation. Each component location on the test vehicles was given a unique reference designator number.

The solder alloys selected for test are:

Sn3.9Ag0.6Cu for reflow and wave soldering (abbreviated as SAC)
Sn3.4Ag1.0Cu3.3Bi for reflow soldering (abbreviated as SACB)
Sn0.7Cu0.05Ni for wave soldering (abbreviated as SnCu)
Sn37Pb for reflow and wave soldering (abbreviated as SnPb)

The SAC alloy was chosen because extensive testing by NEMI suggests it is a viable candidate for use in lead-free commercial electronics. The SACB alloy was chosen because it was the best performer in the large 2001 NCMS study[3]. The SnCu alloy was chosen because it has been widely used in Asia with good results. Finally, SnPb was included to act as the control alloy.

The test vehicles were divided into two types. The first type (named "Manufactured" test vehicles) were made using a laminate with a high glass transition temperature (Tg of 170 degrees C) and an immersion silver board finish. The "Manufactured" test vehicles were meant to be representative of a printed wiring assembly (PWA) designed for manufacture using lead-free solders and lead-free reflow and wave soldering profiles. Tables 1 and 2 list the components used on the "Manufactured" test vehicles and "Manufactured" control test vehicles; the finish on each component; and the solders used. The CLCC's with a lead-free pad finish were produced by robotic dipping of gold-plated CLCC's into the respective molten solders (Sn3.9Ag0.6Cu or Sn3.4Ag1.0Cu3.3Bi). The robotic dipping was done at Corfin Industries in Salem, NH.

The second type (named "Rework" test vehicles) were made using a laminate with a low glass transition temperature (Tg of 140 degrees C) and a tin/lead HASL board finish. The "Rework" test vehicles were meant to be representative of a typical tin/lead PWA that will have to be reworked using lead-free solders in the future. The "Rework" test vehicles were initially built using tin/lead solder and a tin/lead board finish and using typical tin/lead reflow and wave soldering profiles. Selected components on the "Rework" test vehicles were then removed; residual tin/lead solder was cleaned from the pads using solder wick; and new components were attached using a lead-free solder. Components on the "Rework" control test vehicles were reworked with tin/lead solder rather than a lead-free solder. In general, solder wire was used for reworking the components. The BGA's, however, were replaced using flux only and the balls were reflowed using a hot air rework station to form the solder joints. All rework was done at BAE Systems in Irving, Texas.

Two hundred and five test vehicles were assembled at BAE Systems in Irving, Texas. One hundred and nineteen of these test vehicles were "Manufactured" PWA's and eighty six were "Rework" PWA's. Eight components were reworked on each of the "Rework" test vehicles (two BGA's; two TSOP's; two PDIP's; and two TQFP-208's).

On the "Manufactured" test vehicles, some CLCC's were finished with SnPb (on the pads and in the castellations) which resulted in lead-free solder joints contaminated with Pb after assembly (i.e., components U9, U13, U22, U46 and U53). In addition, some of the TSOP's had a SnPb finish which also resulted in lead-free solder joints contaminated with Pb (i.e., components U16, U24, U26, U40 and U62). This mixing was done intentionally in order to determine the effects of lead-contamination upon lead-free solder reliability. Inductively coupled plasma (ICP) spectroscopy was used by Boeing to quantify the amount of Pb in the solder joints on two of the "Manufactured" test vehicles (see Table 3; Test Vehicle ID #'s 80 and 119). The solder joints were removed with a scalpel, dissolved in acid, and the solution was analyzed by ICP spectroscopy.

Similarly, on the "Rework" test vehicles, all of the solder joints contained Pb. The components that were reworked using lead-free solders picked up residual Pb from the pads on the test vehicles (i.e., TSOP's U12 and U25; BGA's U4 and U18; PDIP's U23 and U59; and TQFP-208's U3 and U57). Other components had lead-free finishes but since they were attached to the "Rework" test vehicles using SnPb solder, the final solder joints contained large amounts of Pb (CLCC's U9, U10, U13, U14, U17, U22, U45, U46, U52, U53; and BGA's U2, U5, U6, U21, U43, U44, U55, U56). Again, inductively coupled plasma (ICP) spectroscopy was used to quantify the amount of Pb in the solder joints on two of the "Rework" test vehicles (see Table 3; Test Vehicle ID #'s 158 and 186).

All of the ICP analyses appeared reasonable with the possible exception of the QFP-208 analysis. The copper content in the QFP-208 solder joints was 6.63% which is higher than expected. It is possible that the excess copper was removed from the test vehicle pads when the solder joints were cut from the test vehicle using a scapel.

OBJECTIVE AND APPROACH

The objective of this study is to determine the effects of thermal cycling (-20°C to +80°C) on the relative reliability of lead-free and tin/lead solder joints (i.e., which solder survives the longest).

Fifteen "Manufactured" test vehicles were delivered to Boeing for thermal cycle testing. No "Rework" test vehicles are being tested with the -20°C to +80°C thermal cycle, however. Before beginning the testing, the break-off coupons (populated with 10 chip resistors and 300 chip capacitors) were removed from the main test vehicles.

The Thermotron thermal cycling chamber being used for this test is shown in Figure 2. The test vehicles are being held vertically in racks (see Figure 3) which allows airflow between the vehicles. The thermal cycle being used is -20°C to +80°C with dwell times of 30 minutes (hot dwell) and 10 minutes (cold dwell) and ramp rates of approximately 9.5°C/minute (cooling) and 7.2°C/minute (heating). Figure 4 shows actual air and test vehicle temperatures recorded during the test.

Each of the 55 components on each test vehicle are being individually monitored using Analysis Tech 256STD Event Detectors (set to a 300 ohm threshold) combined with Labview-based data collection software (Figure 5). In addition, the ten 1206 chip resistors on each break-off coupon are being individually monitored. The chip capacitors on the break-off coupons are not being electrically monitored but coupons are being periodically removed from the test so that microsections can be prepared.

For those component types that have a significant number of failures, Weibull plots of the failure data will be created to determine the beta (slope) and the characteristic lifetime (time to fail 63.2% of the population, also called alpha or eta) for each component type.

Using the following equation, the number of cycles required to fail a specific percentage of components, F(t), can be calculated if alpha and beta are known.

$$tp = \alpha\ [-\ln\{1-F(t)*0.01\}]^{1/\beta}$$

RESULTS ("MANUFACTURED" TEST VEHICLES)
At the time this paper was written, 11,100 thermal cycles had been completed. All of the ceramic leadless chip carriers (CLCC's) and TSOP's have failed. All of the contol BGA's (SnPb solder/SnPb balls); control TQFP-144's (SnPb solder/Sn component finish); and the mixed technology BGA's (lead-free solder/SnPb balls) have also failed. It is expected that 15,000 cycles will be accumulated before the test is terminated. The goal is to produce enough failures of each component type so that the data can be used to verify reliability models that are being developed for SnPb and lead-free solders.

CLCC-20's ("Manufactured" Test Vehicles)
When used with CLCC's, SACB is much more reliable than SAC which in turn is more reliable than SnPb. A Weibull plot of the data is shown in Figure 6.

Contamination of the SAC and SACB solder joints with Pb (approximately 17%) reduced the reliability of both solders with SACB exhibiting the greatest reduction. The early failure of the SACB solder joints is presumably due to the formation of a low melting ternary 16Sn32Pb52Bi alloy (m.p. 96°C)[4].

TSOP-50's ("Manufactured" Test Vehicles)
With TSOP's, SACB and SAC demonstrated equivalent reliability and both solders were more reliable than SnPb (Figure 7).

Contamination of the SACB solder joints with Pb (from a SnPb component finish) resulted in a dramatic reduction in reliability, presumably due to the formation of the low melting ternary 16Sn32Pb52Bi alloy (m.p. 96°C). The amount of Pb in these solder joints was approximately 3% as determined by ICP spectroscopy. By comparison, the effects of Pb contamination on the SAC solder joints was much smaller.

BGA-225's ("Manufactured" Test Vehicles)
At 11,100 cycles, all of the contol BGA's (SnPb solder/SnPb balls) and the mixed technology BGA's (lead-free solder/SnPb balls) have failed. In contrast, not a single lead-free BGA (lead-free solder/SAC balls) has failed. Therefore, SACB and SAC solder (combined with SAC solder balls) are both more reliable than SnPb.

SAC solder combined with SnPb balls had greatly reduced reliability compared to the SnPb controls as evidenced by a very low beta value. SACB solder combined with SnPb balls had a population that failed very early and a population that had reliability numbers equivalent to the SnPb controls. A Weibull plot of the BGA data is shown in Figure 8.

TQFP-144's ("Manufactured" Test Vehicles)
With the TQFP-144's (Sn finish), both SACB and SAC solders have greater reliability than SnPb although the lead-free solders have few failures at this point (Figure 9).

PUBLISHED RELIABILITY DATA
A literature search was conducted to collect published Weibull parameters for SnPb and lead-free solders (mainly SAC) used with various component types. The data from the literature search showed that SnPb solder outperforms SAC when the solders are used with components that have a large CTE mismatch with the printed wiring board laminate (e.g., CLCC's and Alloy 42 TSOP's) and tested using a thermal cycle with a large delta T (e.g., -55°C to 125°C). The assumption is that conditions that highly stress the solder joints by maximizing the CTE difference between the PWB and the component will favor SnPb over SAC. Conversely, conditions that minimize the stress put on the solder joints (e.g., compliant components such as BGA's and/or a thermal cycle with a small delta T) will favor SAC over SnPb.

In support of this assumption, J.P. Clech analyzed the available literature data and was able to demonstrate that with shear strains of greater than 6.2%, SnPb is more reliable than SAC while the reverse is true with lesser shear strains[5].

These observations raise the question "Which thermal cycle will give test results that best predict the behavior of solders under field conditions?" The best answer is that models need to be developed (and verified with thermal cycle test data from this and other tests) which can be used to accurately predict field lifetimes for lead-free solders used with different component types. A verified model will allow field lifetimes to be predicted for any component on any board design.

CONCLUSIONS AND RECOMMENDATIONS

Under the conditions of this test, Sn3.9Ag0.6Cu (SAC) and Sn3.4Ag1.0Cu3.3Bi (SACB) are always more reliable than eutectic SnPb regardless of component type (CLCC, TSOP, BGA or TQFP-144).

It has been shown that conditions that highly stress the solder joints by maximizing the CTE difference between the PWB and the component will favor SnPb over SAC[5]. Conversely, conditions that minimize the stress put on the solder joints (e.g., compliant components such as BGA's and/or a thermal cycle with a small delta T) will favor SAC over SnPb. The current test falls into the latter category and we can say with some confidence that the lead-free alloys will outperform SnPb under field conditions that are even less stressful than the -20 to +80^{o}C thermal cycle test.

Models need to be developed (and verified with actual thermal cycle test data from this and other tests) which can be used to accurately predict field lifetimes for lead-free solders used with different component types. A verified model will allow field lifetimes to be predicted for any component on any board design.

Contamination of the SACB solder joints with Pb resulted in a dramatic reduction in reliability, presumably due to the formation of the low melting ternary 16Sn32Pb52Bi alloy (m.p. 96°C). By comparison, the effects of Pb contamination on the SAC solder joints was much smaller. To ensure maximum reliability, SACB solder should not be used when there is a chance that it may be mixed with SnPb solder.

ACKNOWLEDGEMENTS

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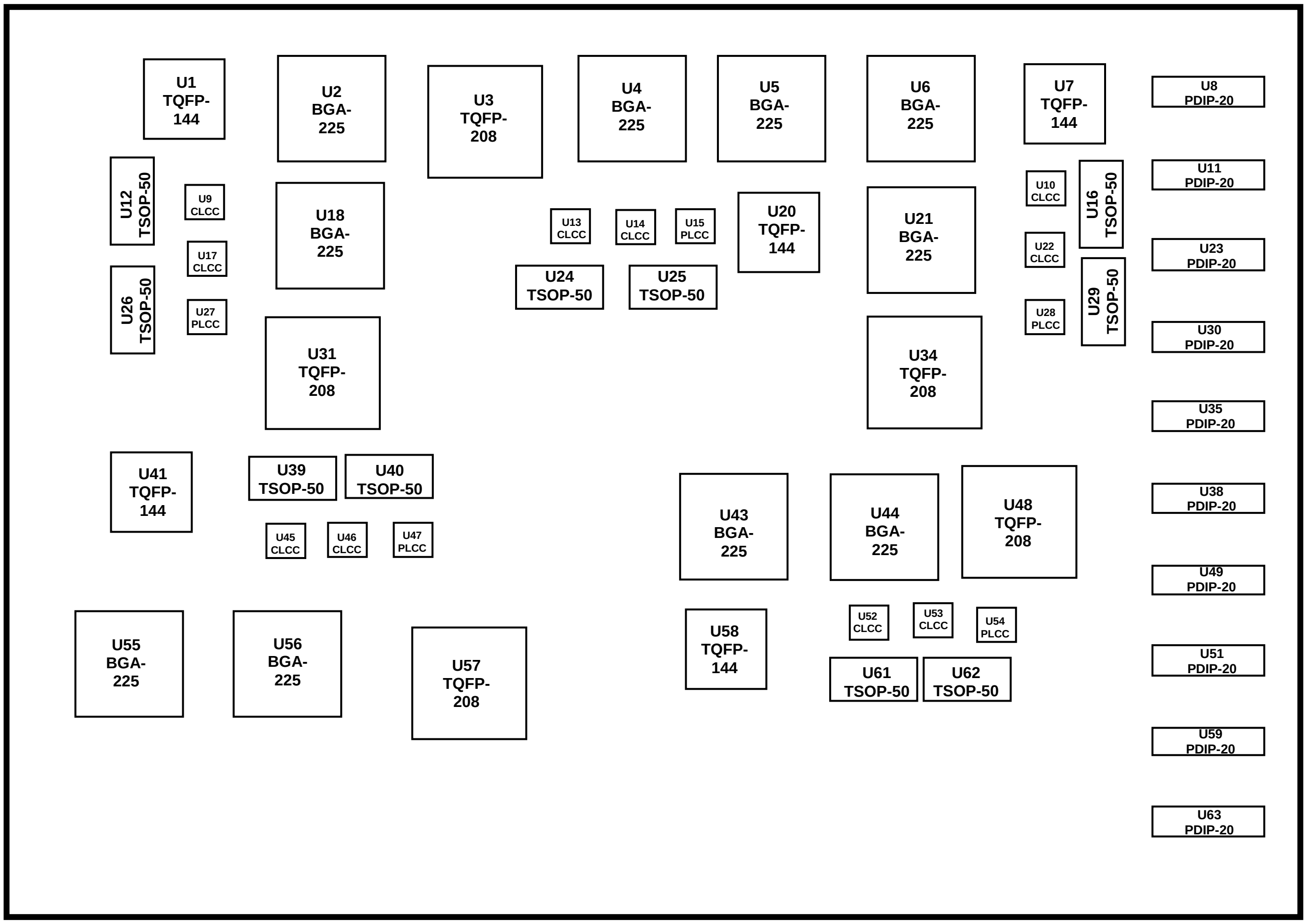

Figure 1. Main Test Vehicle Schematic

Figure 2. Thermal Cycle Chamber

Table 1. Test Vehicle Key ("Manufactured" Test Vehicles – Controls)

Test Vehicle ID Numbers: 20 through 24

Reference Designator	Component	Component Finish	Reflow Solder Alloy	Wave Solder Alloy (DIP's only)
U1	TQFP-144	Sn	SnPb	
U2	BGA-225	SnPb	SnPb	
U3	TQFP-208	NiPdAu	SnPb	
U4	BGA-225	SnPb	SnPb	
U5	BGA-225	SnPb	SnPb	
U6	BGA-225	SnPb	SnPb	
U7	TQFP-144	Sn	SnPb	
U8	PDIP-20	NiPdAu		SnPb
U9	CLCC-20	SnPb	SnPb	
U10	CLCC-20	SnPb	SnPb	
U11	PDIP-20	Sn		SnPb
U12	TSOP-50	SnPb	SnPb	
U13	CLCC-20	SnPb	SnPb	
U14	CLCC-20	SnPb	SnPb	
U15	PLCC-20	Sn	SnPb	
U16	TSOP-50	SnPb	SnPb	
U17	CLCC-20	SnPb	SnPb	
U18	BGA-225	SnPb	SnPb	
U19	CSP-100	SnPb	SnPb	
U20	TQFP-144	Sn	SnPb	
U21	BGA-225	SnPb	SnPb	
U22	CLCC-20	SnPb	SnPb	
U23	PDIP-20	NiPdAu		SnPb
U24	TSOP-50	SnPb	SnPb	
U25	TSOP-50	SnPb	SnPb	
U26	TSOP-50	SnPb	SnPb	
U27	PLCC-20	Sn	SnPb	
U28	PLCC-20	Sn	SnPb	
U29	TSOP-50	SnPb	SnPb	
U30	PDIP-20	Sn		SnPb
U31	TQFP-208	NiPdAu	SnPb	
U32	Hybrid-30	SnPb	SnPb	
U33	Hybrid-30	SnPb	SnPb	
U34	TQFP-208	NiPdAu	SnPb	
U35	PDIP-20	NiPdAu		SnPb
U36	CSP-100	SnPb	SnPb	
U37	CSP-100	SnPb	SnPb	
U38	PDIP-20	Sn		SnPb
U39	TSOP-50	SnPb	SnPb	
U40	TSOP-50	SnPb	SnPb	
U41	TQFP-144	Sn	SnPb	
U42	CSP-100	SnPb	SnPb	
U43	BGA-225	SnPb	SnPb	
U44	BGA-225	SnPb	SnPb	
U45	CLCC-20	SnPb	SnPb	
U46	CLCC-20	SnPb	SnPb	
U47	PLCC-20	Sn	SnPb	
U48	TQFP-208	NiPdAu	SnPb	
U49	PDIP-20	NiPdAu		SnPb
U50	Hybrid-30	SnPb	SnPb	
U51	PDIP-20	Sn		SnPb
U52	CLCC-20	SnPb	SnPb	
U53	CLCC-20	SnPb	SnPb	
U54	PLCC-20	Sn	SnPb	
U55	BGA-225	SnPb	SnPb	
U56	BGA-225	SnPb	SnPb	
U57	TQFP-208	NiPdAu	SnPb	
U58	TQFP-144	Sn	SnPb	
U59	PDIP-20	NiPdAu		SnPb
U60	CSP-100	SnPb	SnPb	
U61	TSOP-50	SnPb	SnPb	
U62	TSOP-50	SnPb	SnPb	
U63	PDIP-20	Sn		SnPb
Break-Off Coupons				
R1	Chip Resistor	Sn	SnPb	
R2	Chip Resistor	Sn	SnPb	
R3	Chip Resistor	Sn	SnPb	
R4	Chip Resistor	Sn	SnPb	
R5	Chip Resistor	Sn	SnPb	
R6	Chip Resistor	Sn	SnPb	
R7	Chip Resistor	Sn	SnPb	
R8	Chip Resistor	Sn	SnPb	
R9	Chip Resistor	Sn	SnPb	
R10	Chip Resistor	Sn	SnPb	
	Chip Capacitors	Sn	SnPb	

Hybrids and CSPs were left off of the test vehicles.

Table 2. Test Vehicle Key ("Manufactured" Test Vehicles)

		Test Vehicle ID Numbers: 90 through 94			Test Vehicle ID Numbers: 129 through 133		
Reference Designator	**Component**	**Component Finish**	**Reflow Solder Alloy**	**Wave Solder Alloy (DIP's only)**	**Component Finish**	**Reflow Solder Alloy**	**Wave Solder Alloy (DIP's only)**
U1	TQFP-144	Sn	Sn3.9Ag0.6Cu		Sn	Sn3.4Ag1Cu3.3Bi	
U2	BGA-225	SnPb	Sn3.9Ag0.6Cu		SnPb	Sn3.4Ag1Cu3.3Bi	
U3	TQFP-208	NiPdAu	Sn3.9Ag0.6Cu		NiPdAu	Sn3.4Ag1Cu3.3Bi	
U4	BGA-225	SnAgCu	Sn3.9Ag0.6Cu		SnAgCu	Sn3.4Ag1Cu3.3Bi	
U5	BGA-225	SnPb	Sn3.9Ag0.6Cu		SnPb	Sn3.4Ag1Cu3.3Bi	
U6	BGA-225	SnAgCu	Sn3.9Ag0.6Cu		SnAgCu	Sn3.4Ag1Cu3.3Bi	
U7	TQFP-144	Sn	Sn3.9Ag0.6Cu		Sn	Sn3.4Ag1Cu3.3Bi	
U8	PDIP-20	NiPdAu		Sn3.9Ag0.6Cu	NiPdAu		Sn0.7Cu0.05Ni
U9	CLCC-20	SnPb	Sn3.9Ag0.6Cu		SnPb	Sn3.4Ag1Cu3.3Bi	
U10	CLCC-20	Sn3.9Ag0.6Cu	Sn3.9Ag0.6Cu		Sn3.4Ag1Cu3.3Bi	Sn3.4Ag1Cu3.3Bi	
U11	PDIP-20	Sn		Sn3.9Ag0.6Cu	Sn		Sn0.7Cu0.05Ni
U12	TSOP-50	SnCu	Sn3.9Ag0.6Cu		SnCu	Sn3.4Ag1Cu3.3Bi	
U13	CLCC-20	SnPb	Sn3.9Ag0.6Cu		SnPb	Sn3.4Ag1Cu3.3Bi	
U14	CLCC-20	Sn3.9Ag0.6Cu	Sn3.9Ag0.6Cu		Sn3.4Ag1Cu3.3Bi	Sn3.4Ag1Cu3.3Bi	
U15	PLCC-20	Sn	Sn3.9Ag0.6Cu		Sn	Sn3.4Ag1Cu3.3Bi	
U16	TSOP-50	SnPb	Sn3.9Ag0.6Cu		SnPb	Sn3.4Ag1Cu3.3Bi	
U17	CLCC-20	Sn3.9Ag0.6Cu	Sn3.9Ag0.6Cu		Sn3.4Ag1Cu3.3Bi	Sn3.4Ag1Cu3.3Bi	
U18	BGA-225	SnAgCu	Sn3.9Ag0.6Cu		SnAgCu	Sn3.4Ag1Cu3.3Bi	
U19	CSP-100	SnAgCu	Sn3.9Ag0.6Cu		SnAgCu	Sn3.4Ag1Cu3.3Bi	
U20	TQFP-144	Sn	Sn3.9Ag0.6Cu		Sn	Sn3.4Ag1Cu3.3Bi	
U21	BGA-225	SnPb	Sn3.9Ag0.6Cu		SnPb	Sn3.4Ag1Cu3.3Bi	
U22	CLCC-20	SnPb	Sn3.9Ag0.6Cu		SnPb	Sn3.4Ag1Cu3.3Bi	
U23	PDIP-20	NiPdAu		Sn3.9Ag0.6Cu	NiPdAu		Sn0.7Cu0.05Ni
U24	TSOP-50	SnPb	Sn3.9Ag0.6Cu		SnPb	Sn3.4Ag1Cu3.3Bi	
U25	TSOP-50	SnCu	Sn3.9Ag0.6Cu		SnCu	Sn3.4Ag1Cu3.3Bi	
U26	TSOP-50	SnPb	Sn3.9Ag0.6Cu		SnPb	Sn3.4Ag1Cu3.3Bi	
U27	PLCC-20	Sn	Sn3.9Ag0.6Cu		Sn	Sn3.4Ag1Cu3.3Bi	
U28	PLCC-20	Sn	Sn3.9Ag0.6Cu		Sn	Sn3.4Ag1Cu3.3Bi	
U29	TSOP-50	SnCu	Sn3.9Ag0.6Cu		SnCu	Sn3.4Ag1Cu3.3Bi	
U30	PDIP-20	Sn		Sn3.9Ag0.6Cu	Sn		Sn0.7Cu0.05Ni
U31	TQFP-208	NiPdAu	Sn3.9Ag0.6Cu		NiPdAu	Sn3.4Ag1Cu3.3Bi	
U32	Hybrid-30	Sn3.9Ag0.6Cu	Sn3.9Ag0.6Cu		Sn3.4Ag1Cu3.3Bi	Sn3.4Ag1Cu3.3Bi	
U33	Hybrid-30	Sn3.9Ag0.6Cu	Sn3.9Ag0.6Cu		Sn3.4Ag1Cu3.3Bi	Sn3.4Ag1Cu3.3Bi	
U34	TQFP-208	NiPdAu	Sn3.9Ag0.6Cu		NiPdAu	Sn3.4Ag1Cu3.3Bi	
U35	PDIP-20	NiPdAu		Sn3.9Ag0.6Cu	NiPdAu		Sn0.7Cu0.05Ni
U36	CSP-100	SnAgCu	Sn3.9Ag0.6Cu		SnAgCu	Sn3.4Ag1Cu3.3Bi	
U37	CSP-100	SnAgCu	Sn3.9Ag0.6Cu		SnAgCu	Sn3.4Ag1Cu3.3Bi	
U38	PDIP-20	Sn		Sn3.9Ag0.6Cu	Sn		Sn0.7Cu0.05Ni
U39	TSOP-50	SnCu	Sn3.9Ag0.6Cu		SnCu	Sn3.4Ag1Cu3.3Bi	
U40	TSOP-50	SnPb	Sn3.9Ag0.6Cu		SnPb	Sn3.4Ag1Cu3.3Bi	
U41	TQFP-144	Sn	Sn3.9Ag0.6Cu		Sn	Sn3.4Ag1Cu3.3Bi	
U42	CSP-100	SnAgCu	Sn3.9Ag0.6Cu		SnAgCu	Sn3.4Ag1Cu3.3Bi	
U43	BGA-225	SnAgCu	Sn3.9Ag0.6Cu		SnAgCu	Sn3.4Ag1Cu3.3Bi	
U44	BGA-225	SnPb	Sn3.9Ag0.6Cu		SnPb	Sn3.4Ag1Cu3.3Bi	
U45	CLCC-20	Sn3.9Ag0.6Cu	Sn3.9Ag0.6Cu		Sn3.4Ag1Cu3.3Bi	Sn3.4Ag1Cu3.3Bi	
U46	CLCC-20	SnPb	Sn3.9Ag0.6Cu		SnPb	Sn3.4Ag1Cu3.3Bi	
U47	PLCC-20	Sn	Sn3.9Ag0.6Cu		Sn	Sn3.4Ag1Cu3.3Bi	
U48	TQFP-208	NiPdAu	Sn3.9Ag0.6Cu		NiPdAu	Sn3.4Ag1Cu3.3Bi	
U49	PDIP-20	NiPdAu		Sn3.9Ag0.6Cu	NiPdAu		Sn0.7Cu0.05Ni
U50	Hybrid-30	Sn3.9Ag0.6Cu	Sn3.9Ag0.6Cu		Sn3.4Ag1Cu3.3Bi	Sn3.4Ag1Cu3.3Bi	
U51	PDIP-20	Sn		Sn3.9Ag0.6Cu	Sn		Sn0.7Cu0.05Ni
U52	CLCC-20	Sn3.9Ag0.6Cu	Sn3.9Ag0.6Cu		Sn3.4Ag1Cu3.3Bi	Sn3.4Ag1Cu3.3Bi	
U53	CLCC-20	SnPb	Sn3.9Ag0.6Cu		SnPb	Sn3.4Ag1Cu3.3Bi	
U54	PLCC-20	Sn	Sn3.9Ag0.6Cu		Sn	Sn3.4Ag1Cu3.3Bi	
U55	BGA-225	SnAgCu	Sn3.9Ag0.6Cu		SnAgCu	Sn3.4Ag1Cu3.3Bi	
U56	BGA-225	SnPb	Sn3.9Ag0.6Cu		SnPb	Sn3.4Ag1Cu3.3Bi	
U57	TQFP-208	NiPdAu	Sn3.9Ag0.6Cu		NiPdAu	Sn3.4Ag1Cu3.3Bi	
U58	TQFP-144	Sn	Sn3.9Ag0.6Cu		Sn	Sn3.4Ag1Cu3.3Bi	
U59	PDIP-20	NiPdAu		Sn3.9Ag0.6Cu	NiPdAu		Sn0.7Cu0.05Ni
U60	CSP-100	SnAgCu	Sn3.9Ag0.6Cu		SnAgCu	Sn3.4Ag1Cu3.3Bi	
U61	TSOP-50	SnCu	Sn3.9Ag0.6Cu		SnCu	Sn3.4Ag1Cu3.3Bi	
U62	TSOP-50	SnPb	Sn3.9Ag0.6Cu		SnPb	Sn3.4Ag1Cu3.3Bi	
U63	PDIP-20	Sn		Sn3.9Ag0.6Cu	Sn		Sn0.7Cu0.05Ni
Break-Off Coupons							
R1	Chip Resistor	Sn	Sn3.9Ag0.6Cu		Sn	Sn3.4Ag1Cu3.3Bi	
R2	Chip Resistor	Sn	Sn3.9Ag0.6Cu		Sn	Sn3.4Ag1Cu3.3Bi	
R3	Chip Resistor	Sn	Sn3.9Ag0.6Cu		Sn	Sn3.4Ag1Cu3.3Bi	
R4	Chip Resistor	Sn	Sn3.9Ag0.6Cu		Sn	Sn3.4Ag1Cu3.3Bi	
R5	Chip Resistor	Sn	Sn3.9Ag0.6Cu		Sn	Sn3.4Ag1Cu3.3Bi	
R6	Chip Resistor	Sn	Sn3.9Ag0.6Cu		Sn	Sn3.4Ag1Cu3.3Bi	
R7	Chip Resistor	Sn	Sn3.9Ag0.6Cu		Sn	Sn3.4Ag1Cu3.3Bi	
R8	Chip Resistor	Sn	Sn3.9Ag0.6Cu		Sn	Sn3.4Ag1Cu3.3Bi	
R9	Chip Resistor	Sn	Sn3.9Ag0.6Cu		Sn	Sn3.4Ag1Cu3.3Bi	
R10	Chip Resistor	Sn	Sn3.9Ag0.6Cu		Sn	Sn3.4Ag1Cu3.3Bi	
	Chip Capacitors	Sn	Sn3.9Ag0.6Cu		Sn	Sn3.4Ag1Cu3.3Bi	

Hybrids and CSPs were left off of the test vehicles.
SnAgCu BGA balls were Sn4.0Ag0.5Cu.

Table 3. Chemical Analysis of Solder Joints Contaminated with Pb (by ICP Spectroscopy)

Component	Ref. Des.	Test Vehicle ID	Reworked?	Component Finish	Board Finish	Solder	%Ag	%Cu	%Pb	%Sn	%Bi	%Au
CLCC	U9	80	no	SnPb	Ag	Sn3.9Ag0.6Cu	2.50	0.72	16.48	80.04	0.05	0.21
CLCC	U9	119	no	SnPb	Ag	Sn3.4Ag1.0Cu3.3Bi	2.23	0.82	16.76	78.07	1.94	0.18
CLCC	U9	158	no	Sn3.9Ag0.6Cu	SnPb	SnPb	1.52	0.62	22.72	75.11	0	0.03
CLCC	U9	186	no	Sn3.4Ag1.0Cu3.3Bi	SnPb	SnPb	1.32	0.57	22.93	73.86	1.30	0.02
TSOP	U26	80	no	SnPb	Ag	Sn3.9Ag0.6Cu	3.67	1.12	2.84	92.36	0.01	0
TSOP	U26	119	no	SnPb	Ag	Sn3.4Ag1.0Cu3.3Bi	3.16	1.98	3.05	89.01	2.80	0
TSOP	U12	158	yes	SnCu	Residual SnPb	Sn3.9Ag0.6Cu	3.31	2.12	0.86	93.71	0	0
TSOP	U12	186	yes	SnCu	Residual SnPb	Sn3.4Ag1.0Cu3.3Bi	2.89	1.98	1.06	91.52	2.55	0
BGA	U55	158	no	Sn4.0Ag0.5Cu	SnPb	SnPb	3.42	0.70	4.37	91.33	0	0.18
BGA	U4	158	yes	Sn4.0Ag0.5Cu	Residual SnPb	Flux Only	3.86	0.88	0.31	94.69	0	0.26
BGA	U4	186	yes	Sn4.0Ag0.5Cu	Residual SnPb	Flux Only	3.81	0.99	0.30	94.66	0	0.24
PDIP	U59	158	yes	NiPdAu	Residual SnPb	Sn3.9Ag0.6Cu	3.50	0.99	2.98	92.53	0	0
PDIP	U59	186	yes	NiPdAu	Residual SnPb	Sn0.7Cu0.05Ni	0	1.04	0.38	98.58	0	0
QFP-208	U3	158	yes	NiPdAu	Residual SnPb	Sn3.9Ag0.6Cu	3.34	6.63*	1.13	88.89	<0.05	<0.05

* Copper may have been removed from pads when solder joints were cut from vehicle

Figure 3. Test Vehicles in Thermal Cycle Chamber

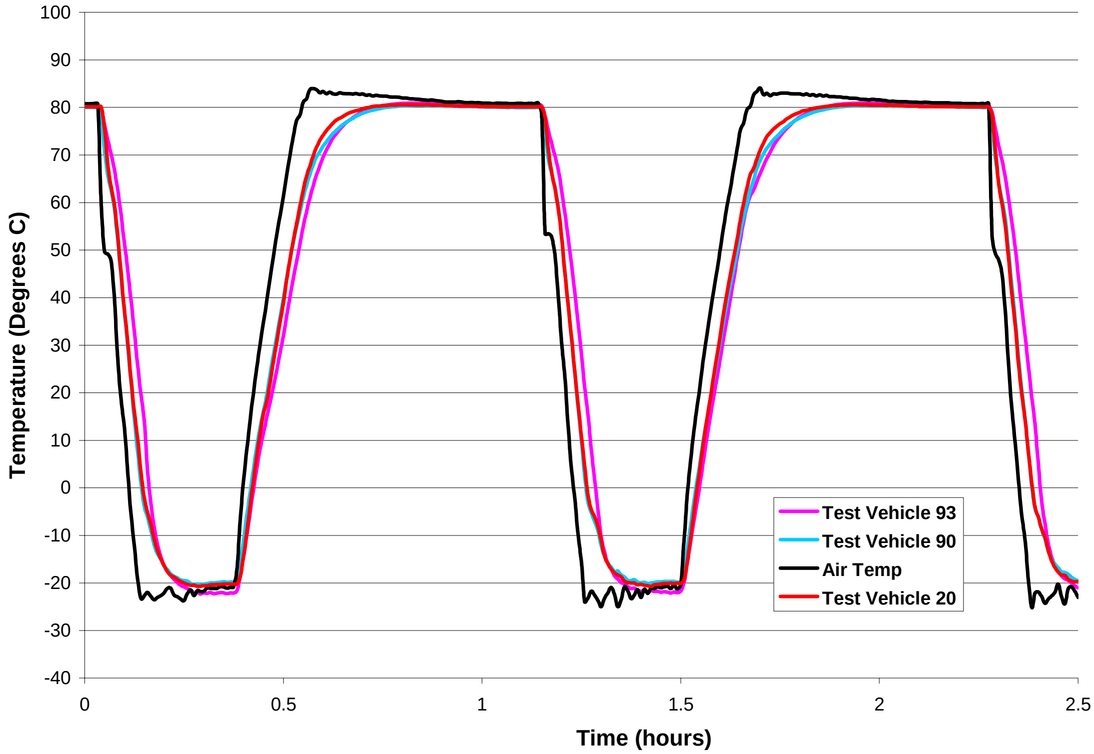

Figure 4. Thermal Cycle (-20°C to +80°C)

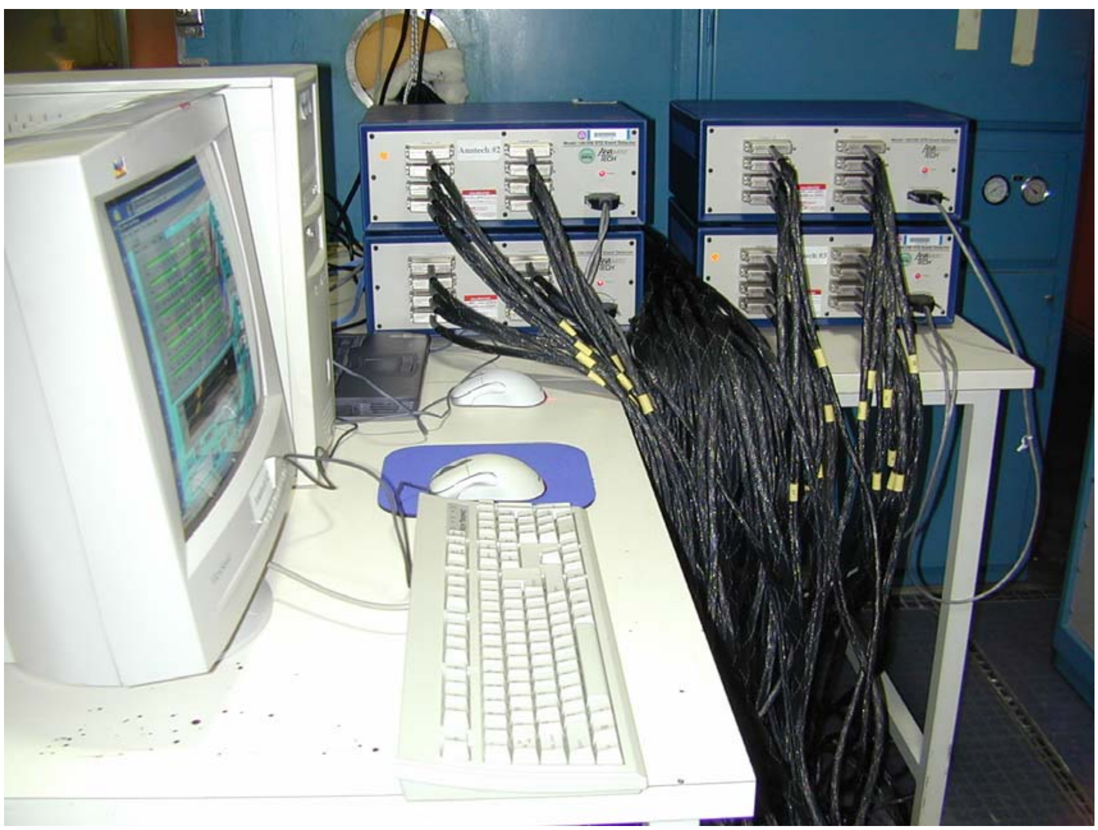

Figure 5. Event Detectors and Data Collection System

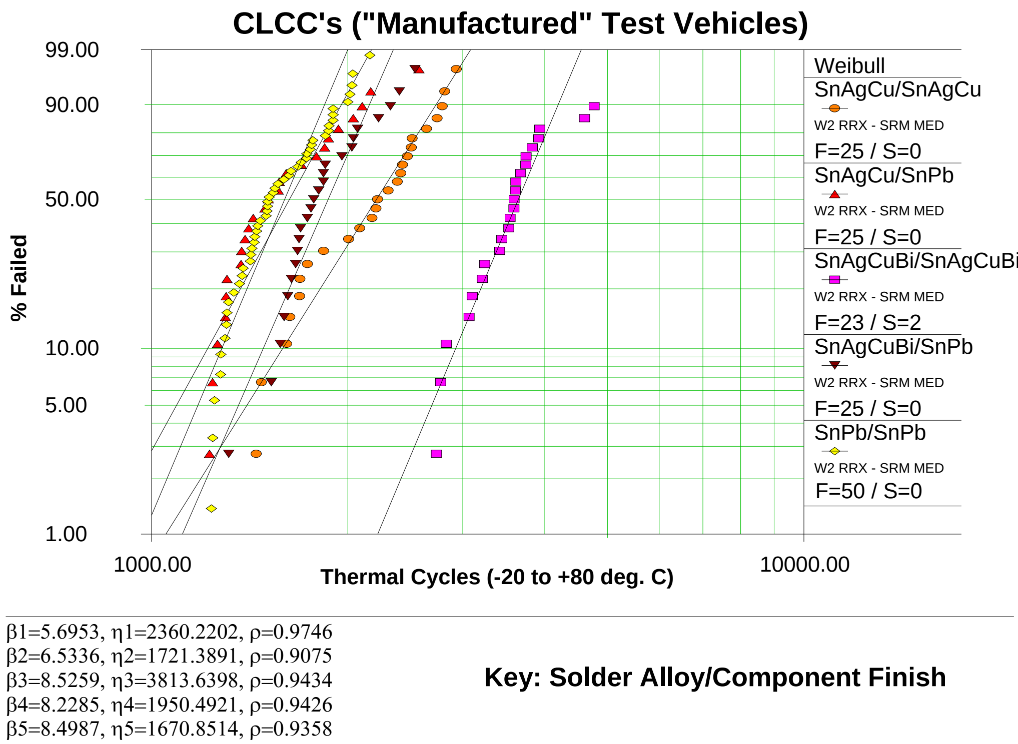

Figure 6. Weibull Plot of CLCC Data ("Manufactured" Test Vehicles)

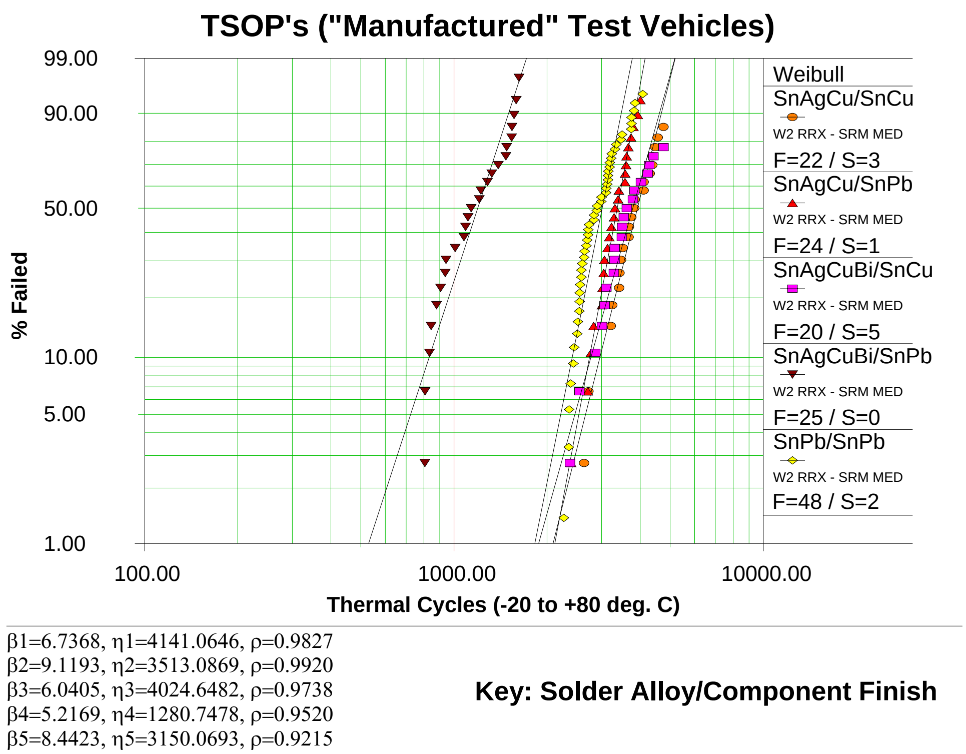

Figure 7. Weibull Plot of TSOP Data ("Manufactured" Test Vehicles)

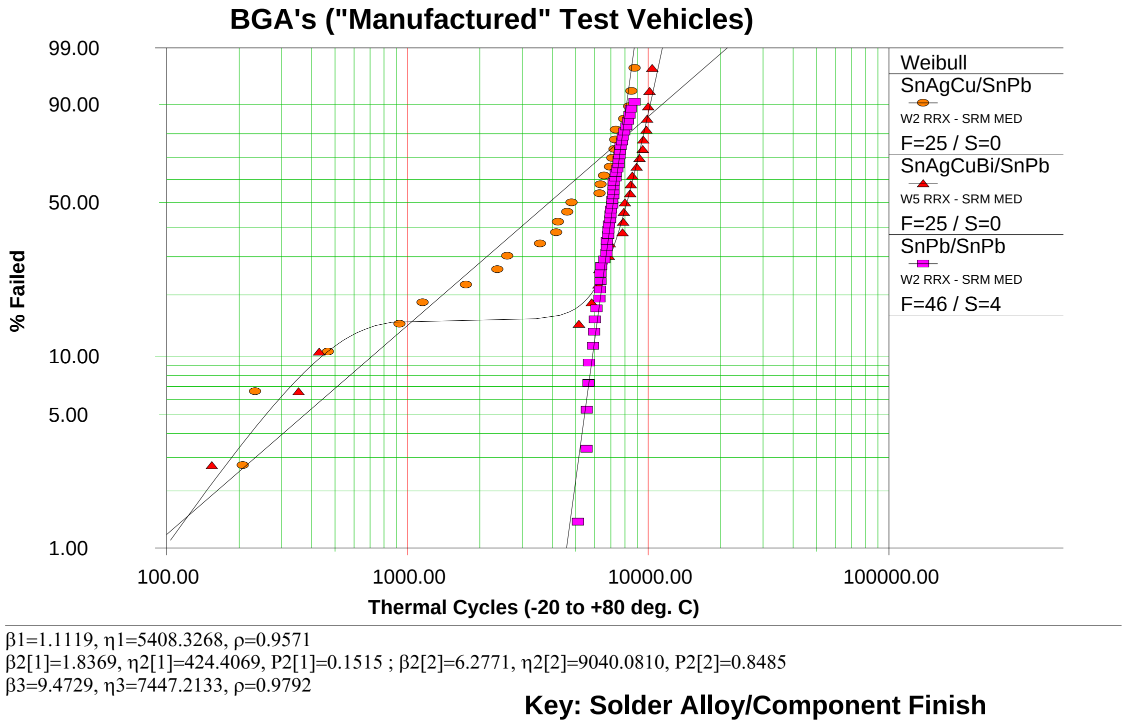

Figure 8. Weibull Plot of BGA Data ("Manufactured" Test Vehicles)

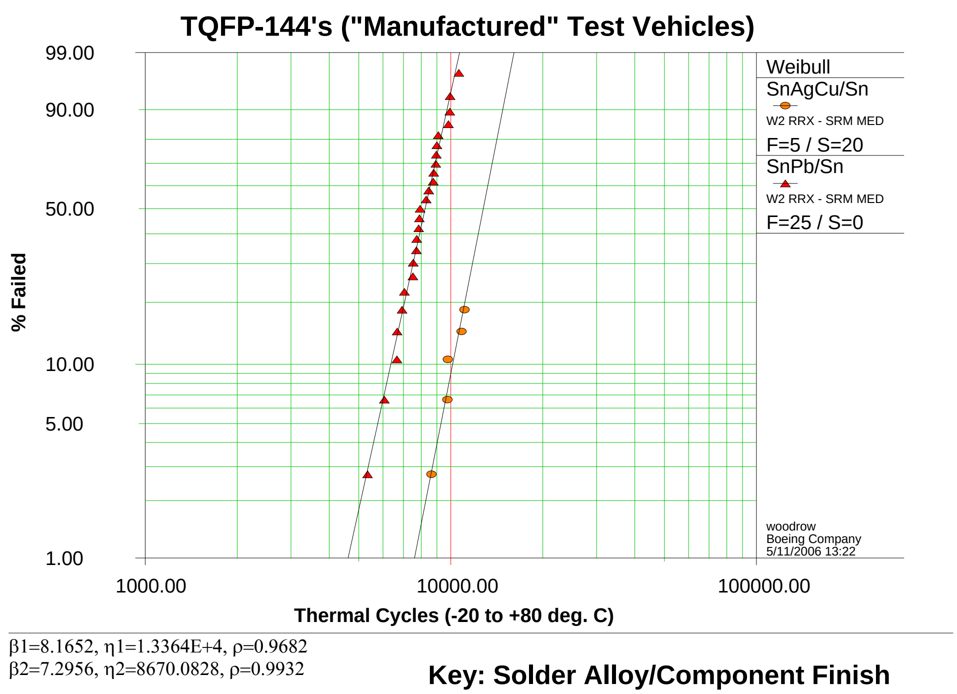

Figure 9. Weibull Plot of TQFP-144 Data ("Manufactured" Test Vehicles)